2015 Indonesian fire activity and smoke pollution show persistent non-linear sensitivity to El Niño-induced drought

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Significance

The 2015 fire season in Indonesia was the most severe observed by the NASA Earth Observing System satellites that go back to the early 2000s in terms of fire activity and pollution. Our estimates show that the 2015 CO_2-equivalent biomass burning emissions for all of Indonesia were in between the 2013 annual fossil fuel CO_2 emissions of Japan and India. Longer-term records of airport visibility in Sumatra and Kalimantan show that 2015 ranked among the worst episodes on record. Analysis of yearly dry season rainfall shows that, due to the continued use of fire to clear and prepare land on degraded peat, the Indonesian fire environment continues to have non-linear sensitivity to dry conditions, and this sensitivity appears to have increased over Kalimantan.

Abstract

The 2015 fire season and related smoke pollution in Indonesia was more severe than the major 2006 episode, making it the most severe season observed by the NASA Earth Observing System satellites that go back to the early 2000s, namely active fire detections from the Terra and Aqua Moderate Resolution Imaging Spectroradiometers (MODIS), MODIS aerosol optical depth, Terra Measurement of Pollution in the Troposphere (MOPITT) carbon monoxide (CO), Aqua Atmospheric Infrared Sounder (AIRS) CO, Aura Ozone Monitoring Instrument (OMI) aerosol index, and Aura Microwave Limb Sounder (MLS) CO. The MLS CO in the upper troposphere showed a plume of pollution stretching from East Africa to the western Pacific Ocean that persisted for two months. Longer-term records of airport visibility in Sumatra and Kalimantan show that 2015 ranked after 1997 and alongside 1991 and 1994 as among the worst episodes on record. Analysis of yearly dry season rainfall from the Tropical Rainfall Measurement Mission (TRMM) and rain gauges shows that, due to the continued use of fire to clear and prepare land on degraded peat, the Indonesian fire environment continues to have non-linear sensitivity to dry conditions during prolonged periods with less than 4mm/day of precipitation, and this sensitivity appears to have increased over Kalimantan. Without significant reforms in land use and the adoption of early warning triggers tied to precipitation forecasts, these intense fire episodes will re-occur during future droughts, usually associated with El Niño events. \body

1. Introduction

The 2015 fire season in Indonesia began in July in Sumatra and a month later in Kalimantan, and was mostly confined to the part of the country in the Southern hemisphere. By September, much of Sumatra and Kalimantan were blanketed in thick smoke that lasted through October, with the haze extending to Singapore, Malaysia and Thailand. Millions of people were exposed to hazardously poor air quality for 2 months (1).

Figure 1 shows the monthly Moderate Resolution Imaging Spectroradiometer (MODIS) active fire detections (described in the next section) between August and November 2015. This period comprised the bulk of the fire season, with 85% of total annual fire detections. September and October were the months with the highest number of active fire detections (68% of total). Most fires burned in the lowlands of southern Sumatra and Kalimantan, often in areas underlain by peat deposits. The locations of the fires and the progression of the fire season resembled 2006, but there were more fires in 2015 in the main fire-affected provinces except for western Kalimantan. The key difference with other years is in the amount of fire activity.

The fire and haze in 2015 was a repeat of events that have occurred periodically in Kalimantan since the 1980s (2-6) and in Sumatra since at least the 1960s (7). From those studies, 1982/83, 1987, 1991, 1994, 1997, and 2006 can be considered 'severe' fire years over Sumatra and Kalimantan, relative to years where little or moderate fire occurs because it is too wet during the dry season for sustained burning. Fires are set to clear logging waste, agricultural waste, and, in order to maintain or secure land-tenure, regrowth (8, 9). The fires often occur on drained and degraded peat lands (10). During abnormally dry years typically associated with El Niño conditions, the peat becomes dry enough to burn (11). Fires on the surface can escape underground, where, because they are so difficult to extinguish and have a large source of fuel, they burn continuously until the return of the monsoon rains (12).

It is widely accepted that the worst event on record was in 1997, with the total CO_2 emissions equivalent to between 13-40% of mean annual global fossil fuel emissions at the time (11). The last major event occurred in 2006 over southern Sumatra and south-central Kalimantan, under a combination of moderate El Niño and positive Indian Ocean Dipole conditions (12). The 2006 burning episode registered uniquely in satellite measurements sensitive to pollution in the mid-troposphere (13-15). In terms of extent and duration, retrieved CO in the upper troposphere in 2006 was the highest during the 2004-2011 observation record across the whole of the tropics (16). There have been brief episodes under isolated dry conditions that produced locally high pollution levels, for example in the central Sumatran province of Riau in 2013 (10), but in general fire activity and pollution levels have not approached those of 2006 in the intervening years.

To quantify the magnitude of 2015 compared to past events and understand the drought conditions under which they occurred, we analyzed data from the NASA Earth Observing System (EOS) period, namely MODIS active fire detections, five different satellite measurements of tropospheric pollution, airport visibility records as a longer-term proxy, and precipitation estimates from satellites and rain gauges. We make the case that the 2015 Indonesian fire season was the most severe season since the NASA's Earth Observing satellite system began observations in the early 2000s, and, by examining visibility data prior to the EOS period, that 2015 ranked

after 1997 and alongside 1991 and 1994 as among the worst Indonesian fire events on record.

2. Data

During the EOS period, we used mid-tropospheric CO data from the Terra Measurement of Pollution in the Troposphere (MOPITT) (17), and Aqua Atmospheric Infrared Sounder (AIRS) instruments (18), and upper-tropospheric CO data from the Aura Microwave Limb Sounder (MLS) (19). Aerosols were characterized using MODIS aerosol optical depth (AOD) over ocean (20) and land (21), and the Aura Ozone Monitoring Instrument (OMI) aerosol index (AI) (22). Fire activity was characterized by Terra and Aqua MODIS active fire detections (23). Details of these data are provided as supplementary information.

At the surface, airport visibility is a useful indicator of severe fire emissions in Indonesia (7, 24-26) because of high emissions per unit area burned and poor ventilation due to typically gentle surface winds. Visibility records were obtained for World Meteorological Organization (WMO)-level surface stations located at three airports in each of southern Sumatra (Rengat, Jambi, and Palembang) and south-central Kalimantan (Pangkalan Bun, Palangkaraya, Muaratewe) from the NOAA Integrated Surface Database for 1990-2015. We computed the total extinction coefficient (B_{ext}) from the visibility using the empirical Koschmieder relationship, $B_{ext} = 1.9/v$, where v is the visibility in km (7). For the sake of computation, reports of zero visibility during the worst of the haze were replaced with 0.05km, the next lowest reported value.

Precipitation estimates for 2000-2015 were obtained from the Tropical Rainfall Measurement Mission (TRMM) (27) 3B42RT product, which is produced using a consistent retrieval, but lacks radar data assimilation after mid-2015. Strictly gauge-based precipitation estimates were obtained for 1990-2015 from the NOAA Climate Prediction Center's global daily precipitation dataset (28).

The MODIS active fire detections, precipitation and extinction coefficient from surface visibility were analyzed over the primary burning regions in southern Sumatra (6°S-0°, 99°E-106°E) and south-central Kalimantan (4°S-0, 110°E-117°E). The OMI AI, MODIS AOD, AIRS CO, MOPITT CO and MLS CO were analyzed separately over Sumatra (10°S-10°N, 90°E-105°E) and Kalimantan (10°S-10°N, 105°E-120°E) to include the larger regions affected by the smoke. A broader pollution signature is seen in the AIRS, MOPITT and MLS CO, but this will require a more thorough examination of transport mechanisms that was beyond the scope of this study.

3. Results

Figure 2 shows the time-evolution of the 2015 event (black) across the satellite data for Sumatra and Kalimantan, compared with the last major event in 2006 (red). All data have been averaged over the previous 7 days.

In southern Sumatra, the 2015 dry season captured by TRMM precipitation began in mid June, with limited fire activity (< 100 detections / day) appearing late in the month and interrupted by brief periods of rain in mid July and early August. Fire activity increased in late August and by early September, 7-day average fire detections varied around 600 / day. Brief rain during the third week of September caused a temporary decrease in fire activity, which was followed by persistently high fire detections until the return of the monsoon in early November.

The increases in MODIS AOD over the larger region including Sumatra lag the increase in fire activity by roughly 10 days but varied around 0.6 for September, increasing slowly through the first three weeks of October. At the end of October, average AOD increased sharply to ~ 1.4. The rapid AOD decrease in early November with the arrival of the monsoon lagged by roughly a week behind the drop in fire activity. Increases in OMI AI followed those in the MODIS AOD, but with the timing of peak values (~0.9) more closely following the peaks in MODIS fire activity in early and late October. A close examination of the OMI AOD retrieval showed that while pixels with low to moderate loading of aerosols were reported as the 'best' quality data, retrievals with higher reflectivity (> 0.3) at 388nm are flagged as less reliable in the AOD inversion. OMI pixels having reflectivity larger than 0.3 directly over the biomass burning are excluded from the retrieval process due to higher reflectivity that is often associated with the clouds. However, the UV-AI is derived and reported for all-sky conditions regardless of reflectivity of the scene.

The signature of the event can be seen in the MOPITT CO retrieval from the surface to 200 hPa, but is particularly distinct at 500 hPa. CO in the mid-troposphere lags behind the increases in fire activity and aerosols through August and September. MOPITT requires cloud-free observations for CO retrievals so many scenes over Indonesia are excluded. Of the remaining high-quality retrievals, CO approached 300ppbv, slightly higher than in 2006, but the amount of missing data in 2015 makes a comparison between years difficult.

The AIRS CO at 500 hPa had less missing data due to greater data coverage and the use of extrapolation to cloud-free radiances prior to the retrieval. By October, CO increased to concentrations as high as 300 ppbv, dropping sharply in early November with the return of the monsoon. The MLS CO at 215 hPa (~12 km in altitude over Sumatra) increased steadily through September, and varied slightly above 200ppbv during the first three weeks of October. A rapid increase to CO exceeding 400 ppbv at the end of October corresponded to the sharp increases in the MODIS AOD. In the uppermost troposphere at 100hPa (~16km), the increase in CO only began in mid October, but rapidly approached 175 ppbv before the end of the burning season.

Fire activity and pollution for 2006 over Sumatra showed similar precipitation-driven timing to 2015, but was overall lower in magnitude and shorter in duration. MLS CO at 215hPa briefly exceeded 200ppbv and at 100hPa mostly remained below 100ppbv. The less severe conditions in 2006 were due to more precipitation from June through mid-September.

Over Kalimantan, the timing of drying, fire activity and tropospheric pollution during 2015 was very similar to that over Sumatra. Fire activity increased in August, varying about 800 detections/day through September. Precipitation in early October caused a temporary decrease in fire activity, MODIS AOD and OMI AI, but was followed in late October by sharp increases similar to Sumatra, particularly in the aerosol-related retrievals. AIRS and MOPITT CO at 500 hPa varied around 225 ppbv for October, with fewer excluded MOPITT profiles than for Sumatra. MLS CO showed an increase in late October, as Sumatra, but to lower CO concentrations, briefly exceeding 300 ppbv at 215 hPa and 150 ppbv at 100 hPa. Compared to 2006, the earlier start of fire activity over Kalimantan in 2015 was offset by an earlier onset of the monsoon. Other than higher CO at 100 hPa, 2015 and 2006 were of comparable magnitude over Kalimantan. Even after the fires stopped with the return of the monsoon, both regions continued to have 100 hPa CO well above "background" (60 ppbv) through November 2015.

This event represents the largest enhancement in the MLS record of CO at 215 hPa (i.e., since August 2004) (Figure 3). The CO peaks approaching 300 ppbv over western Indonesia form part of a broad signature stretching from the western Indian Ocean to the southwest Pacific Ocean, exceeding the extent, magnitude and duration of the 2006 event. High (200 ppbv) is also measured regularly over eastern South America (boxes Sa11 and Sb11) due to burning in the Arc of Deforestation around the Southeastern Amazon and the Cerrado (savanna) further south, but the upper tropospheric CO signature has a much smaller extent than over Indonesia.

Figure 4 shows the extinction coefficient (B_{ext}) for 2015 along with 1991 and 1997. 1994 was also a severe burning year prior to the EOS period and is discussed in the next section. B_{ext} is computed using visibility from three weather stations in each of southern Sumatra and south-central Kalimantan's main burning regions over which fire activity and precipitation was averaged in Figure 2. Over Sumatra in 2015, the B_{ext} peaks in mid-September and early and late October correspond closely to those seen in fire activity in Figure 2, reinforcing the usefulness of airport visibility as a severe haze indicator in Indonesia. The 2015 B_{ext} increase is more severe and longer in duration than 2006 but is much lower than the 1991 and 1997 episodes. The magnitude of the 1997 event reflects much lower antecedent rainfall beginning in June. The later 1991 peak in early October compared to 1997 was due to significant rainfall in early September. The late October interruption in haze in 1991 also followed significant precipitation. Overall, B_{ext} data indicates that the 2015 haze in southern Sumatra was less severe than 1991 or 1997, which is easy to explain for 1997 given the decreased precipitation that year during the exceptionally strong El

Niño. However, it is more difficult to explain for 1991, which was only slightly drier than 2015.

In Kalimantan, 2015 B_{ext} has two peaks in late September and late October that correspond to those in fire activity. 2015 B_{ext} was also lower than 1997 due to the near-absence of precipitation that year between mid July and early October. The early September onset of 2015 haze was comparable to that in 1991 and its termination earlier, but with weaker isolated precipitation events than in 1991, making it slightly more severe.

Across the satellite observations, we can conclude with a fair amount of certainty that 2015 was a worse fire year than 2006, because of its earlier start in Sumatra, higher fire activity in September over Kalimantan, and despite an earlier end in Kalimantan. There is greater uncertainty associated with the visibility-based B_{ext} record due to possible changes in observing procedures and more missing records in the early 1990s, but the available data suggest more severe 1990s burning in Sumatra compared to 2015, and in Kalimantan less severe burning in 2015 than in 1997 but more than 1991.

To give a more complete picture of the relationship between annual fire or pollution magnitude and the underlying dry conditions, Figure 5 shows the annual mean dry season (August-November) precipitation plotted against the different fire and haze indicators, for all years over which each source of data are available. Mean precipitation is averaged over the previous 12 weeks to include the effects of antecedent drying for each month during the dry season. In each case, we estimated the strength of the non-linear relationship using piecewise linear regression, which includes an estimated change-point parameter α. We interpret α as the precipitation threshold below which fire and pollution magnitude increase rapidly, and above which, conditions are too wet for high fire activity and pollution. The estimates of α also provide an empirical means of separating severe from non-severe fire years.

There is a consistently non-linear relationship between dry season precipitation and the different indicators of fire and pollution. Across all indicators of fire and haze during the EOS period, the estimates of α ranged from 3.9 mm/day to 5.2 mm/day. That is, for average dry-season precipitation greater than 6mm/day, there is little fire activity or pollution. Between 4-6 mm/day, there is some increase in fire and pollution, and below 4mm/day, fire and pollution increase rapidly. This has been seen before over broadly the same regions for MODIS fire detections (29) and the MODIS-based Global Fire Emissions Database (12). The non-linearity was also seen between seasonal precipitation in B_{ext}, depending on the period considered for Sumatra and Kalimantan (7).

During the EOS period, the non-linear relationship with precipitation is strongest (R^2 between 0.85 and 0.98 depending on the region) for MODIS AOD, AIRS and MOPITT CO at 500 hPa, and MODIS fire detections. It is still present, but weaker (R^2 between 0.69 and 0.90) for the OMI AI, and MLS CO at both levels, presumably due

to their higher-altitude retrieval sensitivity, and therefore additional dependence on a vertical transport mechanism, which has been examined for Indonesian biomass burning using different transport models (30-32). The greatest separation between Sumatra and Kalimantan is for the MLS 215 hPa CO and precipitation relationships. We speculate that at this altitude, pollutant concentrations are strongly dependent on nearby deep convection, but that higher at 100 hPa, there is a greater influence of horizontal advection and the subsequent mixing of pollutants between the two regions. This is supported by a parameterized case study (32) for the 2006 event, in which the convective supply of CO from the surface peaked at 200 hPa, and was very limited at 100 hPa.

For the longer-term B_{ext} haze proxy, there is a strong non-linear relationship with precipitation over Sumatra (R^2=0.90), which weakens over Kalimantan (R^2=0.77). This difference is due to a weaker linear relationship over Kalimantan for years with seasonal precipitation below the estimated 3.7mm/day threshold, which is discussed further below.

Discussion

Fire activity is known to increase in the tropics during droughts, as long as fuels are abundant (33). But the consistency and non-linearity of this relationship in Indonesia across such a diverse set of satellite-based measurements during the EOS era is remarkable. We are unaware of any other large region where interannual variation in fire activity and pollution through the depth of the troposphere is so strongly, and non-linearly, related to the dry conditions on the ground. The uniqueness of the relationship for Indonesia is due to the ubiquitous use of fire that grows out of control during droughts, its large area of degraded peatlands, and, presumably, the strong control that precipitation has over whether the peat becomes dry enough to burn (34).

The B_{ext} plot in Figure 5 suggests an increase in fire sensitivity over Kalimantan since the 1990s. Despite occurring under comparably dry, or even wetter conditions, the burning in 2006, 2015, and also 2002, was more severe than in 1991 and 1994, which is what weakens the non-linear relationship with precipitation compared to Sumatra. This would represent a continuation of an increase in fire sensitivity over Kalimantan (7). That increase was the result of an absence of severe fire in the 1960s and 1970s despite regularly occurring drought years. Severe fire appeared only in the 1980s, and strengthened in the 1990s, which was attributed to intensifying land use change (7). In southern Sumatra, 2015 and 2006 were somewhat less severe than 1994 despite similar seasonal rainfall, perhaps suggesting a decrease in fire sensitivity. This could correspond to an increase in fire prevention and suppression on larger industrial plantations in the provinces of South Sumatra and Jambi, or to a northward shift in the intensiveness of fire, as noted by recent case studies during the secondary dry season in Riau province (10, 12) and satellite records of tree-cover loss (35). Possible changes in fire sensitivity inferred from B_{ext} will need to be studied further, taking into account changes in data completeness, the effect of different year-to-year transport patterns relative to

the airport locations, and most importantly, corroboration with estimates of changing land use.

Since 1997, annual emissions from fires in all of Indonesia have been between 6 (in 2010) and 1046 (in 1997) Tg C according to the Global Fire Emissions Database version 4s (GFED4s), updated from previous versions (36). Total emissions for 2015 were estimated to be 380 Tg C, which translates to 1.5 billion metric tons CO_2 equivalent when also including emissions of methane and nitrous oxide. This is in between the 2013 annual fossil fuel CO_2 emissions of Japan and India (37). Known sources of uncertainty in the emissions estimate are a possible underestimation of burned area due to cloud and smoke cover (38) and a possible overestimation relating to recent work (39, 40) showing that the depth of peat burning decreases for successive fires, which is not yet taken account for repeated fires in the same area in GFED4s. Viewed historically, these events are nevertheless a large part of what makes Indonesia's land use change-related greenhouse gas emissions much larger than its fossil fuel emissions when compared to other countries (41).

Eliminating fire from degraded peatlands is a long-term goal and will require major reforms in land use and land tenure in the context of Indonesia's need for economic development. In the short term, fire prevention, suppression and mitigation measures must be tied to early warning triggers. Our analysis over five different indicators of fire activity and atmospheric pollution from NASA EOS data suggests that doing so is a matter of being able to anticipate extended periods of less than 4mm/day of rain. Given the skill with which strong El Niño impacts can increasingly be predicted (42, 43) tying these predictions to early warning triggers based on these types of precipitation thresholds should be a priority.

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Figures

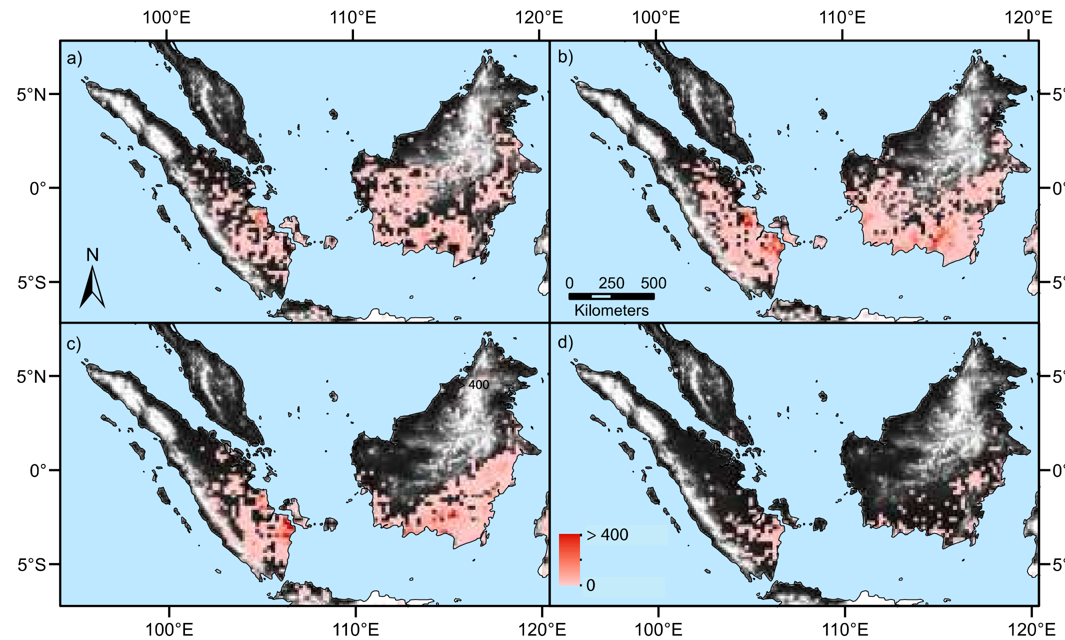

Figure 1. 2015 high confidence Aqua and Terra MODIS active fire density (0.25 ° × 0.25 °) over Sumatra and Borneo for a) August, b) September, c) October and d) November.

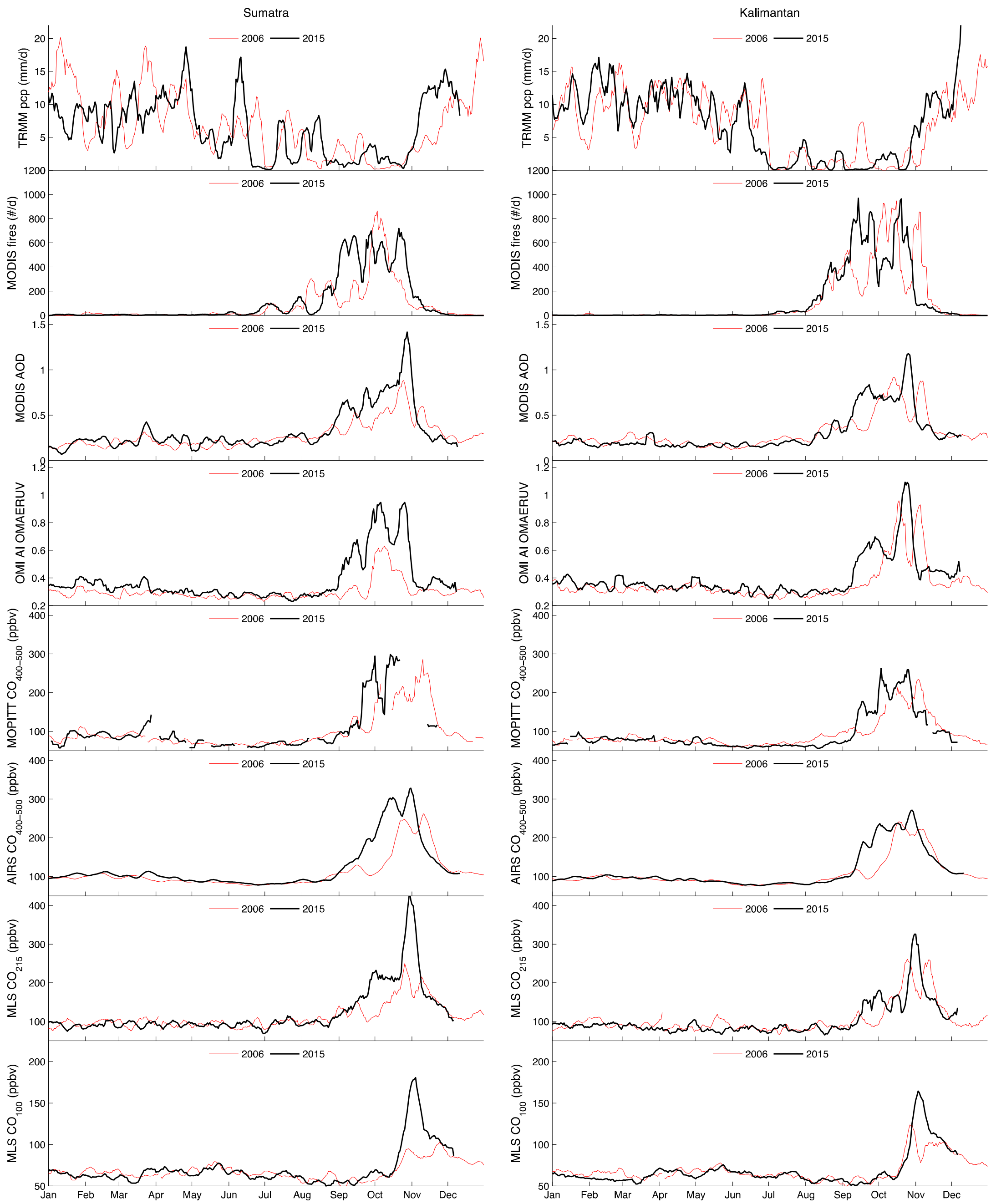

Figure 2. Time series of various species for 2015 and 2006 over Sumatra and Kalimantan. OMI AI, MODIS AOD, MOPITT CO, AIRS CO and MLS CO are averaged for Sumatra over (10S-10N, 90E-105E) and for Kalimantan over (10S-10N, 105E-120E). MODIS active fires and TRMM precipitation are averaged over the smaller primary burning regions, for Sumatra (6S-0, 99E-106E) and for Kalimantan (4S-0, 110E-117E). Subscripts for the MLS, AIRS and MOPITT CO are the altitude in hPa over which the data were analyzed. All data have been averaged over the previous 7 days.

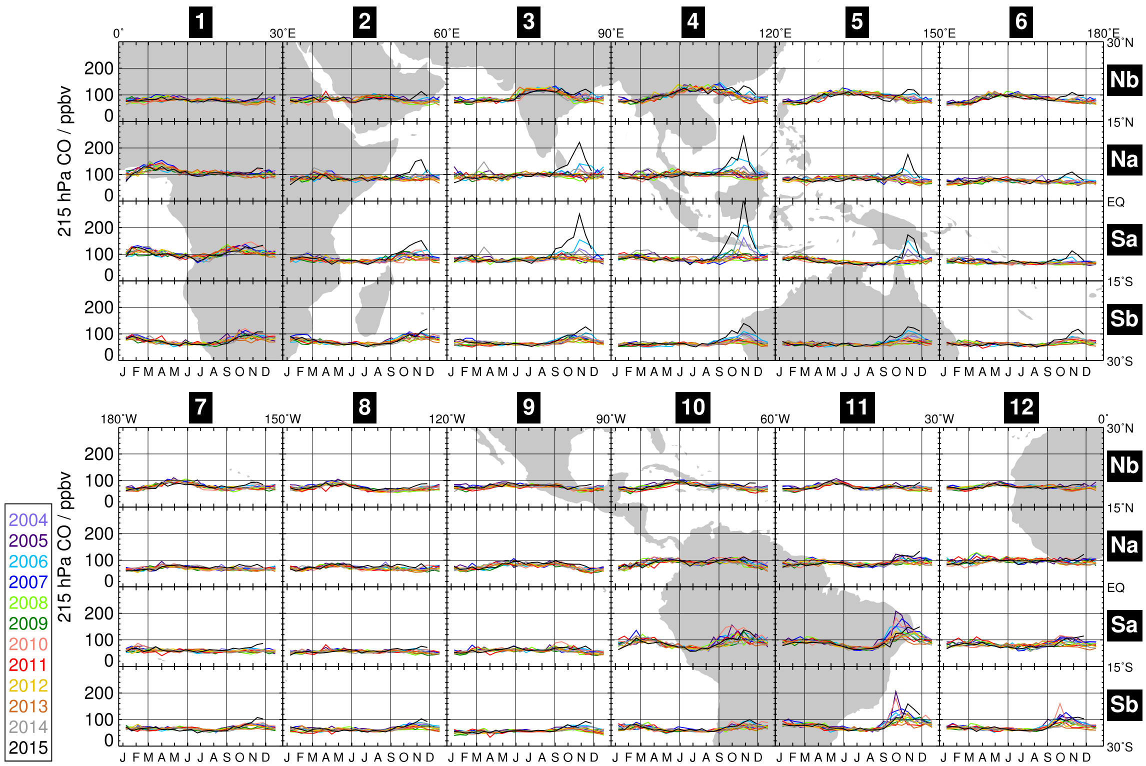

Figure 3. Bi-weekly averaged MLS CO at 215 hPa (~12km) for 15° x 30° cells during 2004-2015. Line colors denote year. Numbers and letters in black boxes along the top and right edges identify regions for discussion in the text.

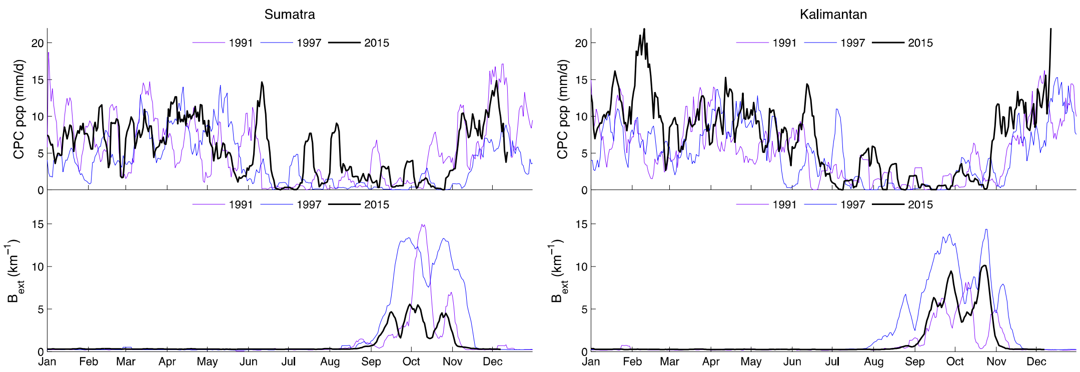

Figure 4. NOAA Climate Prediction Center (CPC) gauged-based precipitation and extinction coefficient (B_{ext}) calculated from horizontal visibility. CPC precipitation averaged over the smaller primary burning regions, for Sumatra (6S-0, 99E-106E) and for Kalimantan (4S-0, 110E-117E) for three high fire years. Extinction coefficient calculated over Sumatra from the airports in Rengat, Jambi and Palembang, and over Kalimantan from Pangkalan Bun, Palangakaraya and Muaratewe. All data have been averaged over the previous 7 days.

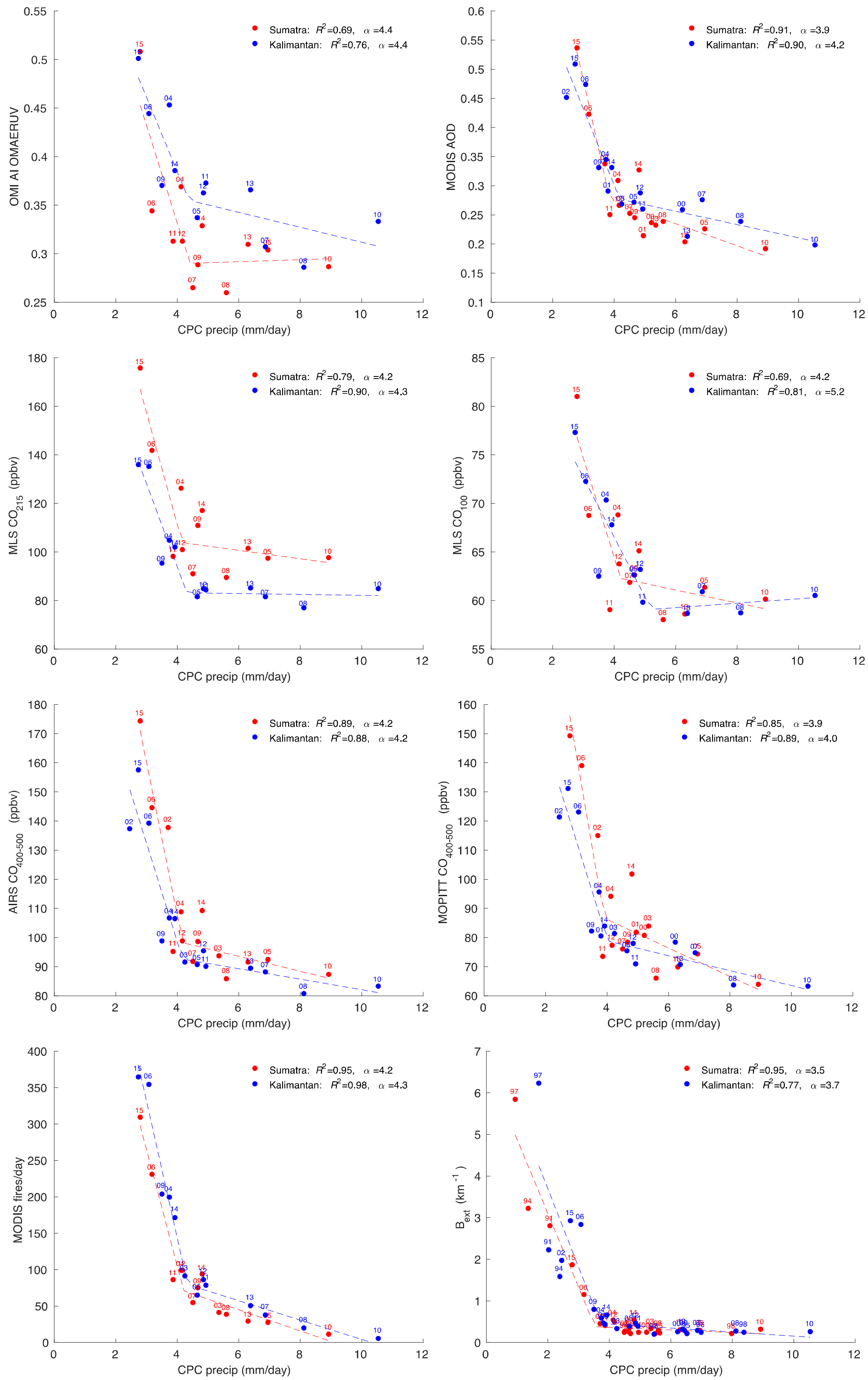

Figure 5. Annual August-November relationships between CPC precipitation over the source regions and fire/pollution metrics. Subscripts for the MLS, AIRS and MOPITT CO are the altitude in hPa over which the data were analyzed. The numbers above each point are the last two digits of each year. Dashed lines show the piecewise-linear regression fit for each region, the coefficient of determination (R^2) and change-point estimate of precipitation (α, mm/day) for which are provided in the figure legends.